Electrical Performance, Reliability Analysis, and Characterization

Tim Burress
Email: burressta@ornl.gov
Phone: 865-946-1216

Oak Ridge National Laboratory
National Transportation Research Center

2017 U.S. DOE Vehicle Technologies Office
Annual Merit Review

June 6, 2017 **Project ID: EDT087**

This presentation does not contain any proprietary, confidential, or otherwise restricted information

ORNL is managed by UT-Battelle
for the US Department of Energy

Overview

Timeline

- **Start – FY17**
- **End – FY19**
- **17% complete**

Barriers

- Integrating custom ORNL inverter-motor-controller with OEM components and optimizing controls for non-linear motors throughout operation range.
- Intercepting, decoding, and overtaking OEM controller area network (CAN) signals.
- Adapting non-standard motor shaft and assembly to dynamometer and test fixture.
- This project helps with program planning and the establishment and verification of all DOE 2020 targets.

Budget

- **Total project funding**
  - **DOE share – 100%**
- **Funding received in FY16: $ 333K**
- **Funding for FY17: $ 184K**

Any proposed future work is subject to change based on funding levels

Partners

- ORNL Team members
  - Lixin Tang
  - Randy Wiles
  - Jason Pries
  - Andy Wereszczak
- ANL
- NREL

Project Objective and Relevance

- **Overall Objective:** The core function of this project is to confirm power electronics and electric motor technology status and identify barriers and gaps to prioritize/identify R&D opportunities
  - Assess design, packaging, and fabrication innovations during teardown of sub-systems
    - Identify manufacturer techniques employed to improve specific power and/or power density
    - Perform compositional analysis of key components
      - Facilitates trade-off comparisons (e.g. magnet strength vs coercivity) and general cost analysis
  - Examine performance and operational characteristics during comprehensive test-cell evaluations
    - Establish realistic peak power rating (18 seconds)
    - Identify detailed information regarding time-dependent and condition-dependent operation
  - Compile information from evaluations and assessments
    - Identify new areas of interest
    - Evaluate advantages and disadvantages of design evolutions
    - Compare results with other EV/HEV technologies and DOE targets
- **FY17 Objective**
  - Complete 2017 Toyota Prius HEV teardown and evaluation

Milestones

Date	Milestones and Go/No-Go Decisions	Status
December 2016	Go/No-Go decision: Identify vehicle subsystems that meet EDT interests.	Go.
March 2017	Milestone: Determine core functionality and general design approach of HEV/EV subsystems.	Complete.
June 2017	Milestone: Perform initial testing on HEV/EV subsystems.	Delayed.
September 2017	Milestone: Complete comprehensive testing of selected subsystem and assess design characteristics and operation with respect to 2020 DOE targets.	Delayed.

Any proposed future work is subject to change based on funding levels

Approach/Strategy

- Provide status of select EV and HEV technologies through assessment of design, packaging, fabrication, and performance during comprehensive evaluation
  - Compare results with other EV and HEV technologies
  - Confirm or provide feedback on VTO targets
  - Identify new areas of interest
  - Evaluate advantages and disadvantages of design changes, e.g., complexity of 3rd generation Prius PCU cooling system
- Foster collaborations with U.S. DRIVE Electrical and Electronics Tech Team (EETT) and Vehicle Systems Analysis Tech Team (VSATT)
- Publish evaluation results and conclusions for open discussion

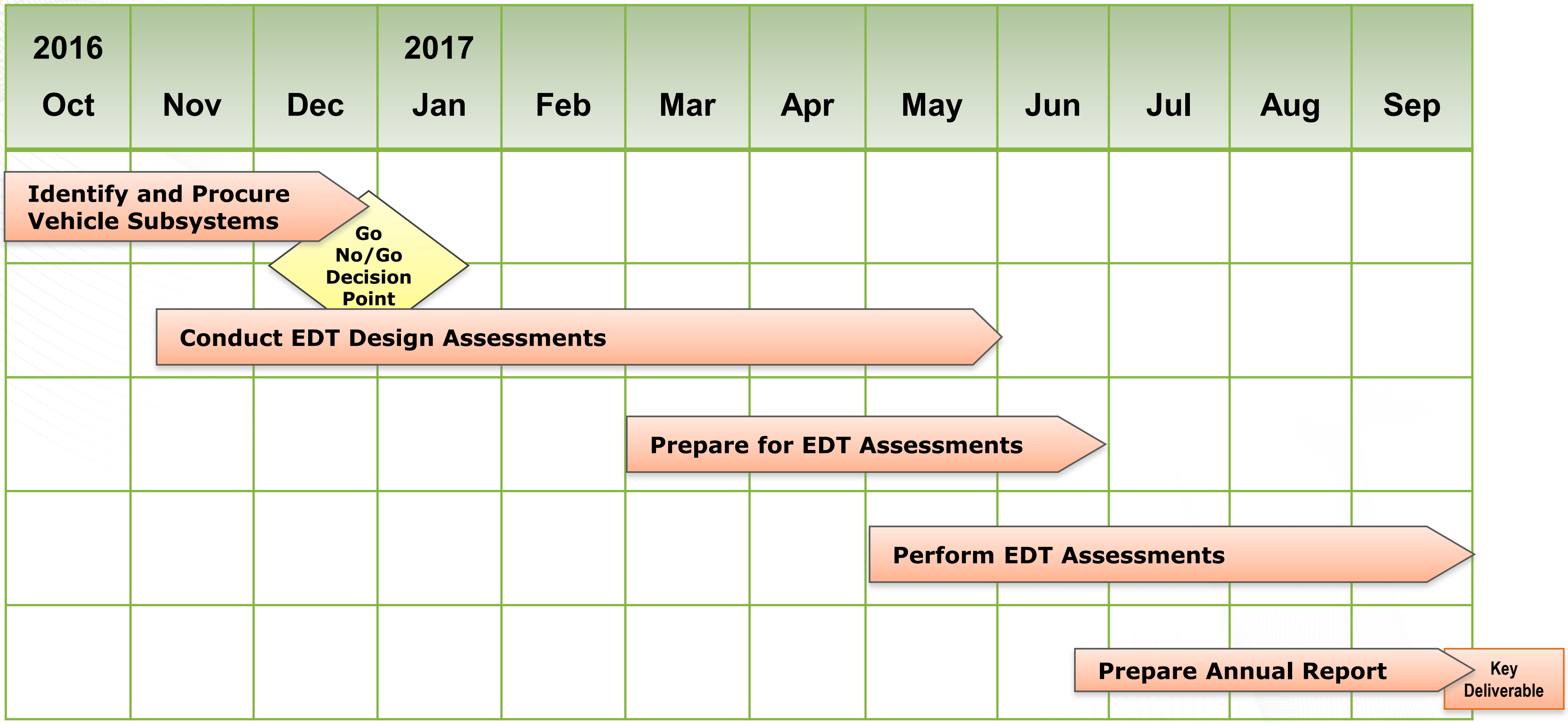
Any proposed future work is subject to change based on funding levels

Approach/Strategy

- Obtain and publish detailed information on state-of-the-art technologies and their progression:
  - Design and functional assessments
    - Magnet and capacitor characteristics
    - Power control unit and electric motor design and packaging
    - Converter (e.g. boost, DC-DC, charger, etc.) design and packaging
    - Mass, volume, and power capabilities of various subsystems
    - Material quantities (e.g. copper mass, NdFeB mass and composition, etc)
    - Power density and specific power
  - Operational characteristics
    - Efficiency maps for motor, inverter, converter, and charger
    - Impact of temperature limits, speed, etc. upon capabilities
    - Continuous duration
      - Time-dependent and condition-dependent information especially important as technologies progress to long duration operation, such as electric vehicles EVs
      - 55 kW for 2 seconds, 2 minutes, or 2 hours?

Any proposed future work is subject to change based on funding levels

Approach FY17 Timeline



Go No/Go Decision Point: Identify vehicle subsystems of interest to EDT.

Key Deliverable: Annual report with findings from evaluations.

Any proposed future work is subject to change based on funding levels

Technical Accomplishments – Previous FYs

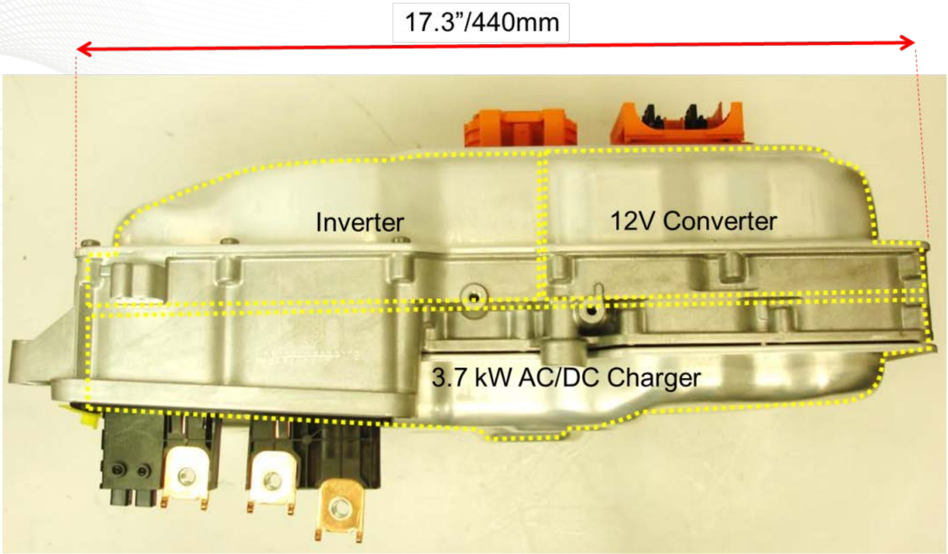
- Compared progressing technologies - 2004 Prius, 2006 Accord, 2007 Camry, 2008 LS 600h, 2010 Prius, 2011 Sonata, 2012 Sonata generator, 2012 LEAF, 2013 LEAF charger, 2013 Camry PCU, 2014 Accord, 2016 BMW i3, and 2017 Prius.

Component & Parameter	2022 DOE Targets (55 kW)	2017 Prius (53 kW)	2016 BMW i3 (125 kW)	2014 Honda Accord (124 kW)	2012 Leaf (80 kW)	2012 Sonata HSG 23 (8.5 kW)	2011 Sonata (30 kW)	2010 Prius (60 kW)	2008 LS600h Lexus (110 kW)	2007 Camry (70 kW)	2013 Camry (105 kW)	2004 Prius (50 kW)
Motor												
Peak pow er density, kW/L	**5.7**	**5.7**	**9.1**	**8.5**	**4.2**	**7.42** (2.7)	**3.0**	**4.8**	**6.6**	**5.9**		**3.3**
Peak specific pow er, kW/kg	**1.6**	**1.7**	**3.0**	**2.9**	**1.4**	**1.9** (0.7)	**1.1**	**1.6**	**2.5**	**1.7**		**1.1**
Inverter												
Excludes generator inverter (parenthetical values exclude boost converter mass/volume for Toyota Vehicles)												
Peak pow er density, kW/L	**13.4**	**11.5 (21.7)**	**18.5**	**12.1 (18.5)**	**5.7**	**5.6** (2.0)	**7.3**	**5.9** (11.1)	**10.6** (17.2)	**7.4** (11.7)	**12.7** (19.0)	**4.5** (7.4)
Peak specific pow er, kW/kg	**14.1**	**8.6 (19.0)**	**14.1**	**9.1 (21.7)**	**4.9**	**5.4** (2.0)	**6.9**	**6.9** (16.7)	**7.7** (14.9)	**5.0** (9.3)	**11.5** (17.2)	**3.8** (6.2)

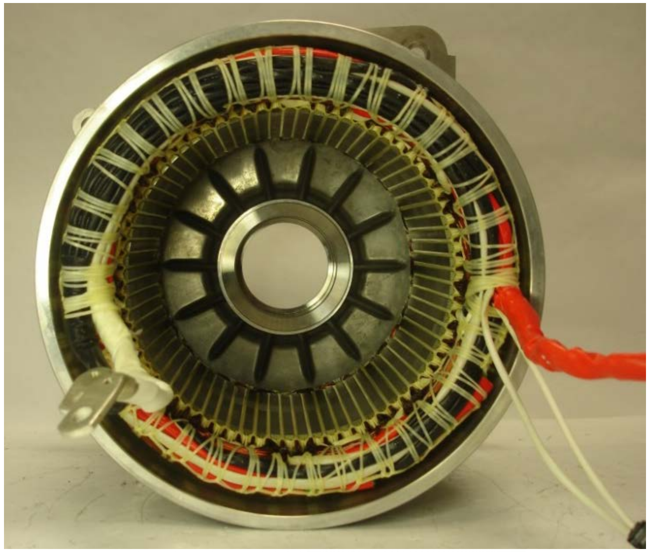
Note: All power density and specific power levels in table are not apples-to-apples. (e.g. LEAF and Sonata have continuous capability near their published rated power)

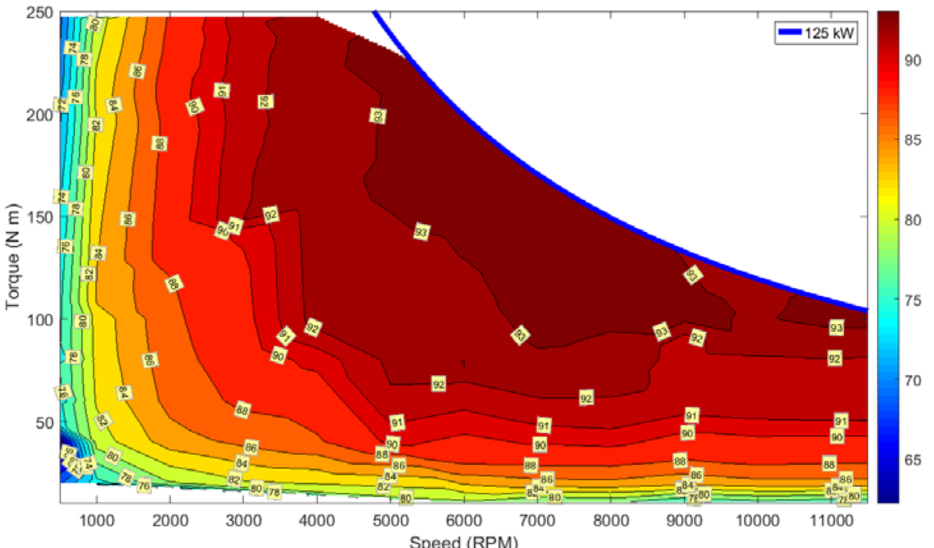
FY16 Accomplishments – 2016 BMW i3 teardown

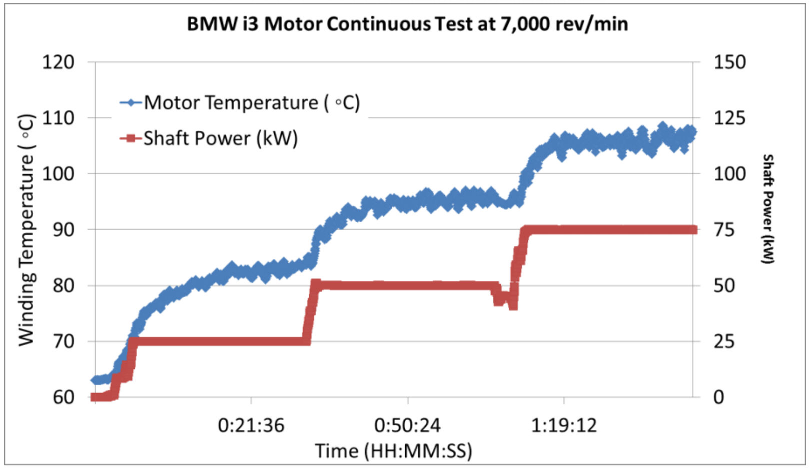
PCU assembly: 19 kg as received



Stator assembly: 42kg, as received
125 kW, 250 Nm



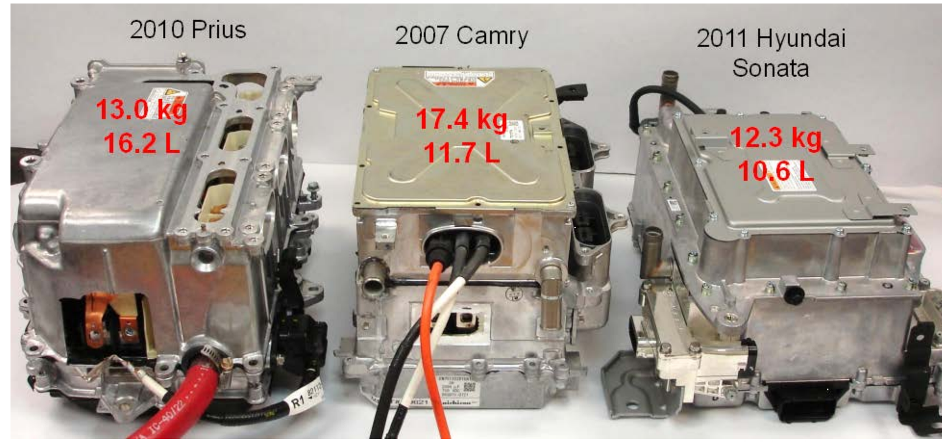




Most points above ~40 N-m and 1,500 rpm are above 86%

FY17 Accomplishments – 2017 Prius PCU

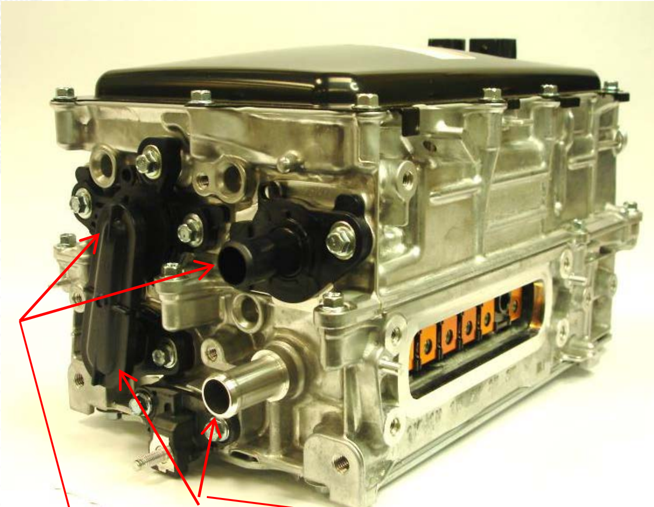
- PCU contains
  - 3-phase motor inverter
  - 3-phase generator inverter
  - Boost converter
  - DC-DC converter (~200VDC to 12VDC)



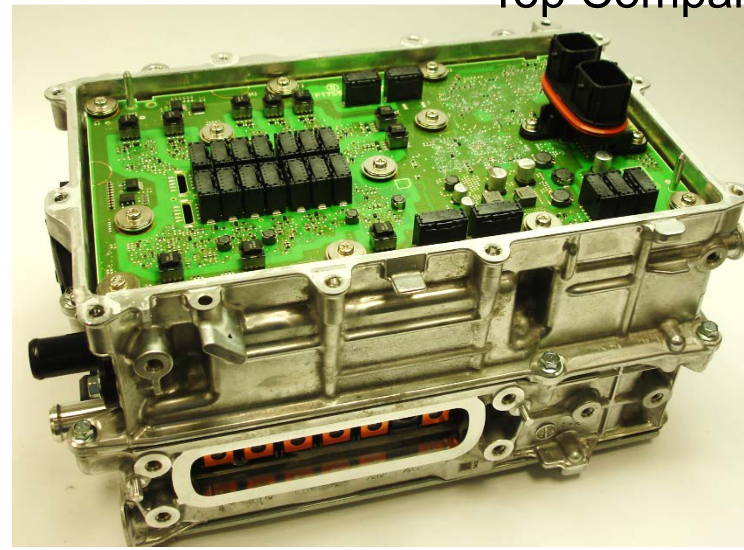
2017 Prius

10.8 kg, 8.4 L as received

FY17 Accomplishments - 2017 Prius PCU



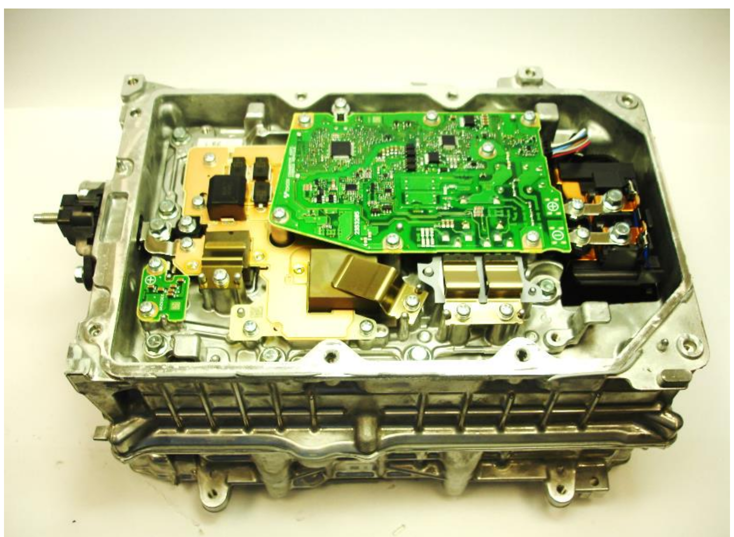
Top Compartment

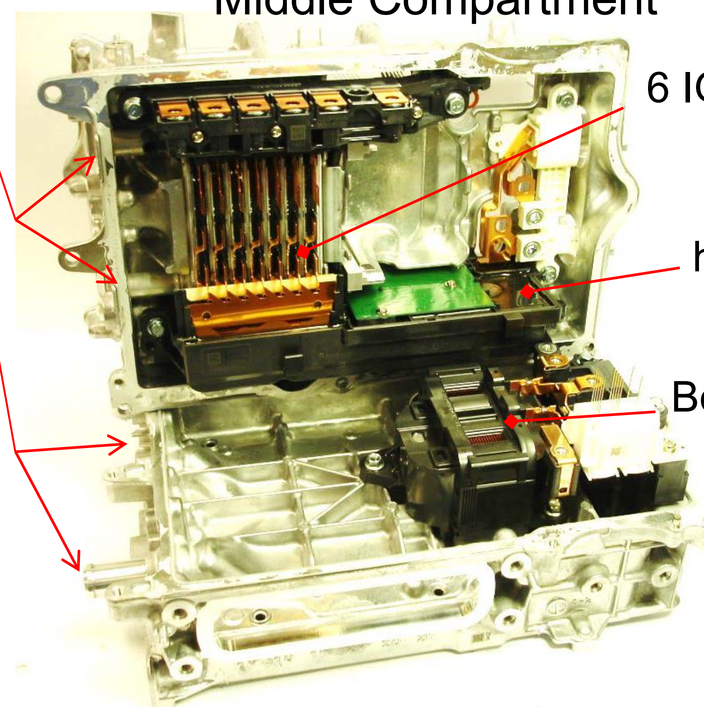


Two cooling loops

Middle Compartment

Bottom compartment (12V converter)





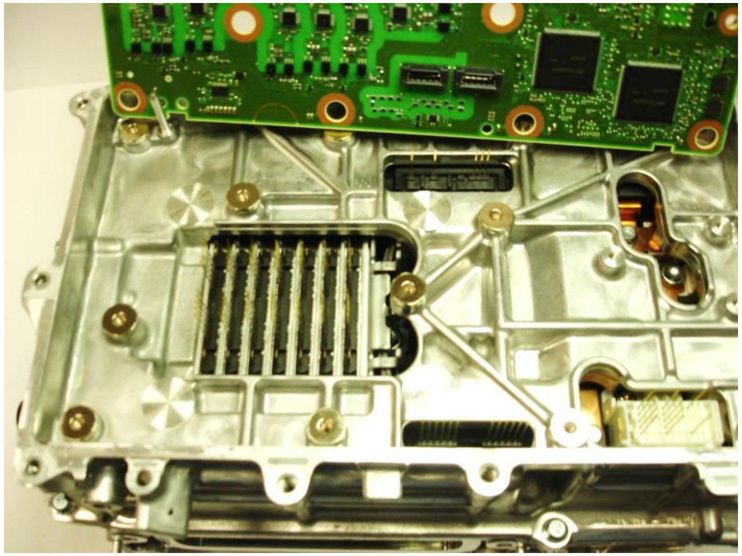
6 IGBT modules

471 μF
high voltage
capacitor

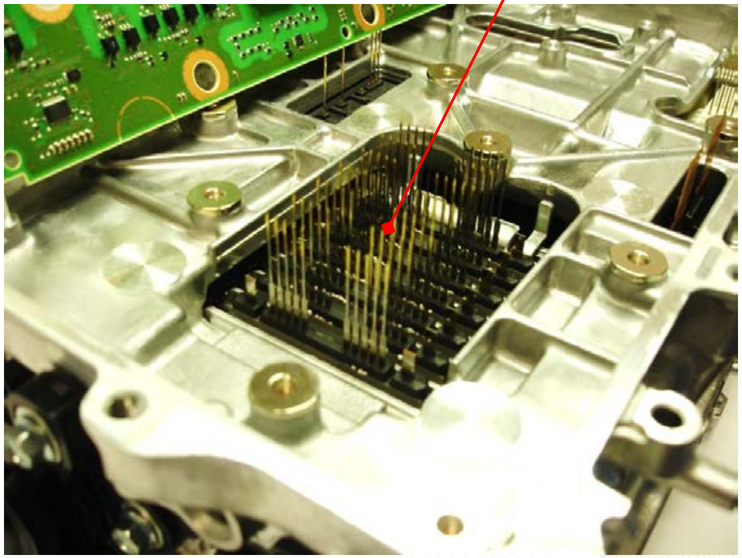
Boost inductor
(1.4 kg)

FY17 Accomplishments

- Upper and lower IGBT/diode combined into one module
- Modules are cooled on both sides
- No switches in parallel
    - Motor inverter has only one upper and one lower IGBT/diode per phase
    - Boost converter has only one upper and one lower IGBT/diode

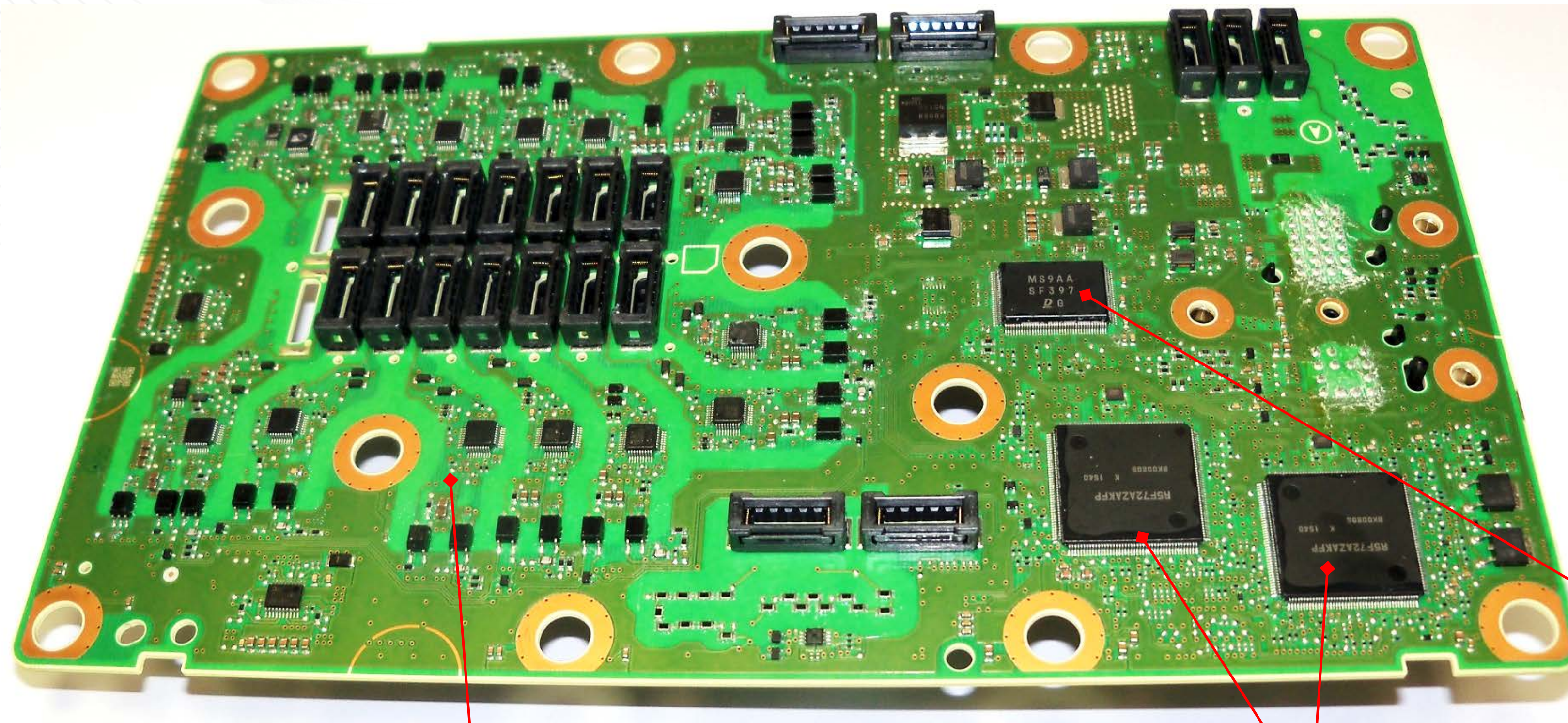


6 IGBT modules



FY17 Accomplishments

Toyota Prius microcontroller and driver circuitry combined onto one board



MS9AA by Denso FPGA?

Three lower devices for generator and motor share same gate drive power supply

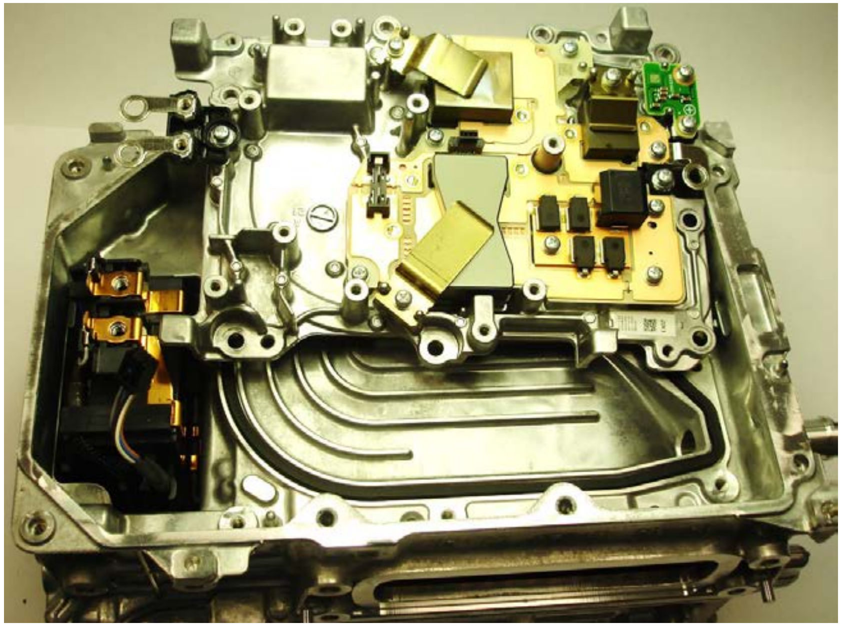
R5F72AZAKFP
32 bit DSP by Renesas?

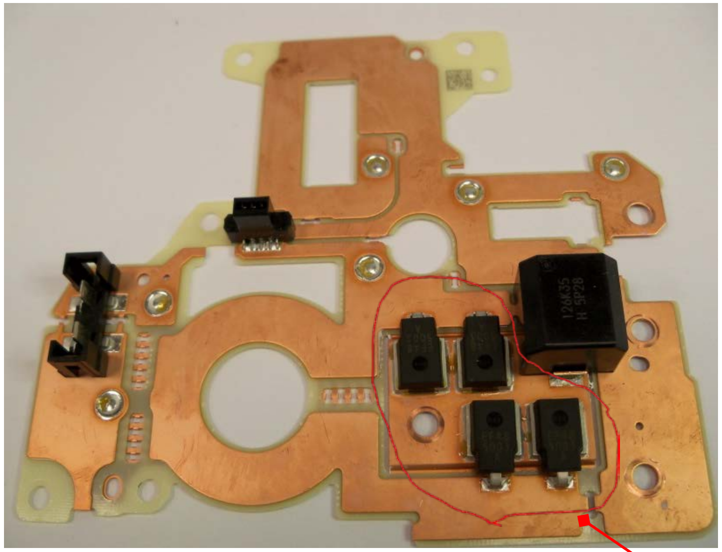
Note: No Tamagawa resolver chip on control board

FY17 Accomplishments

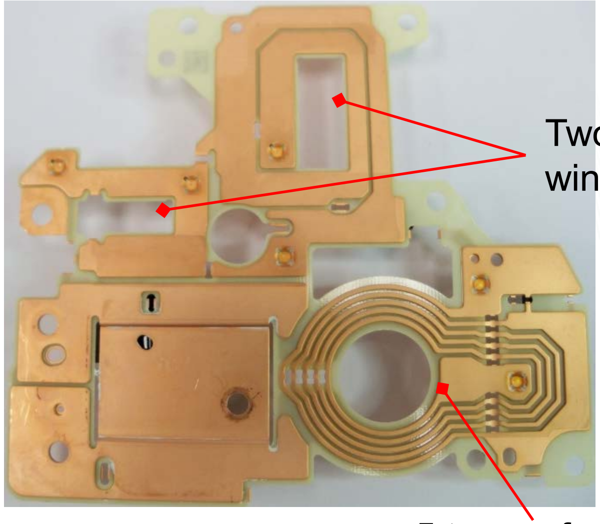
- 12V converter is directly cooled by water-ethylene glycol
- Inductor and transformer windings implemented directly on circuit board

Bottom compartment (12V converter)





EF48 Diodes



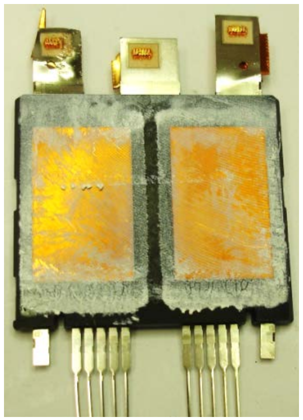
Two inductor windings

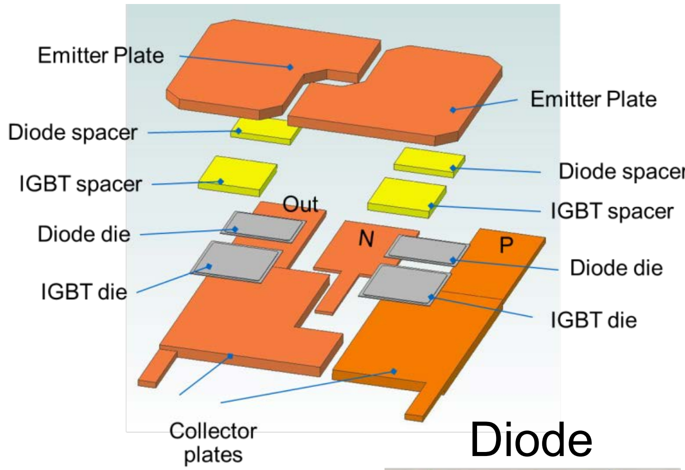
5 turns of primary side winding

FY17 Accomplishments – Prius Power Module

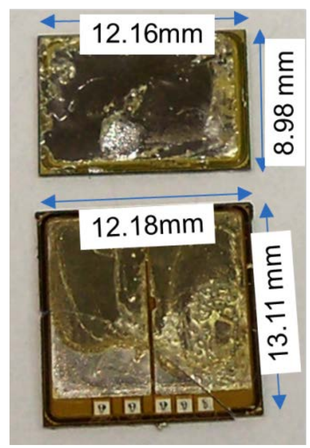
Motor inverter, generator inverter, and boost converter have no parallel devices

Motor Inverter Phase Leg Module

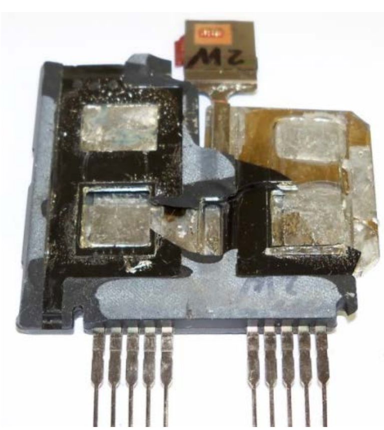


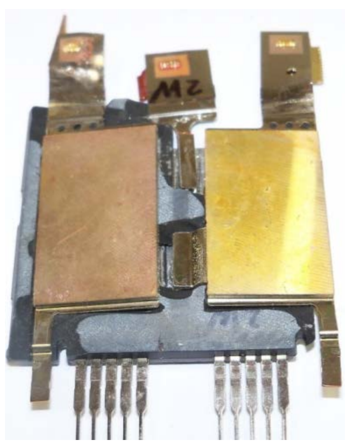


Diode



IGBT





Cross-sectional area:

- Motor IGBT
  - ~12.18 x 13.11 mm
  - Device: ~159.7 mm^2
  - Inverter total: ~958.1 mm^2
- Motor Diode
  - ~12.16 x 8.98 mm
  - Device: ~109.2 mm^2
  - Inverter total: ~655.2 mm^2

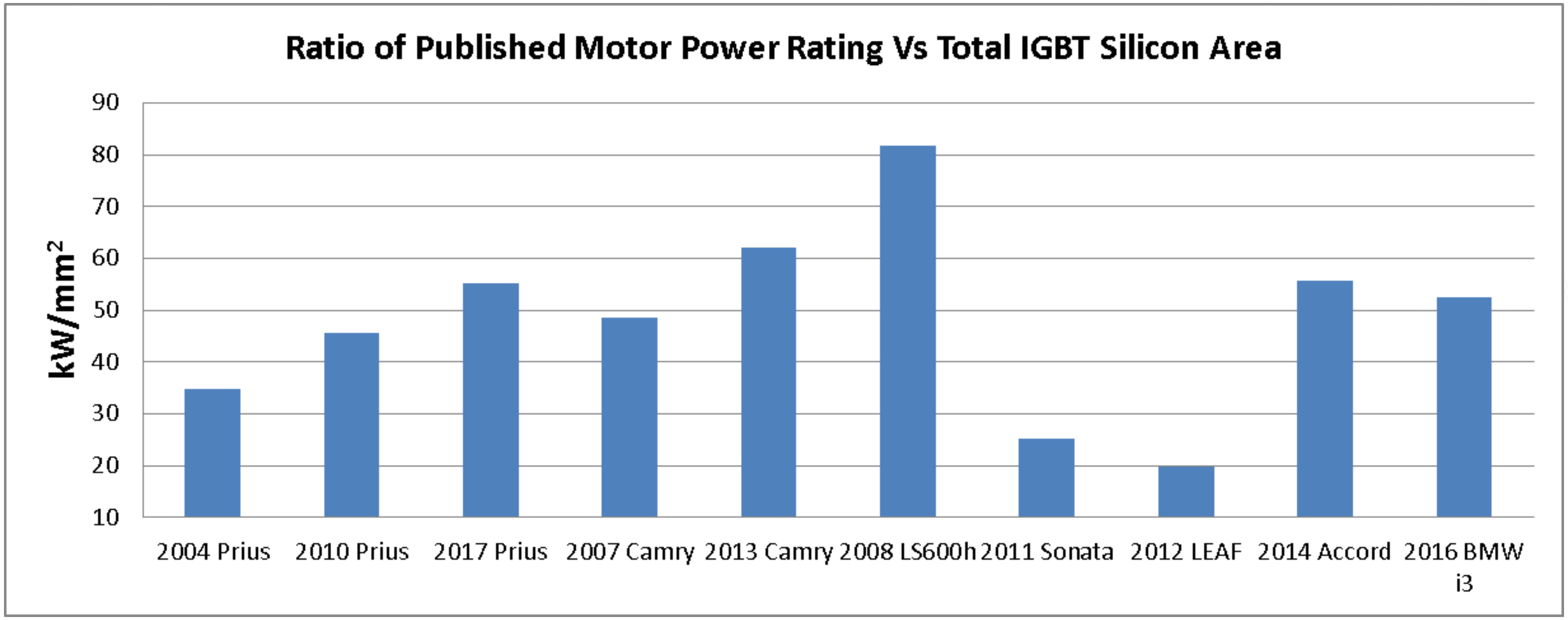
- Generator IGBT
  - ~8.77 x 8.98 mm
  - 78.75 mm^2
- Generator Diode
  - ~8.11 x 6.91 mm
  - 56.0 mm^2

- Boost IGBT
  - ~14.22 x 14.16 mm
  - 201.4 mm^2
- Boost diode
  - ~8.88 x 14.18 mm
  - 125.9 mm^2

FY17 Accomplishments - Comparisons of Device Area

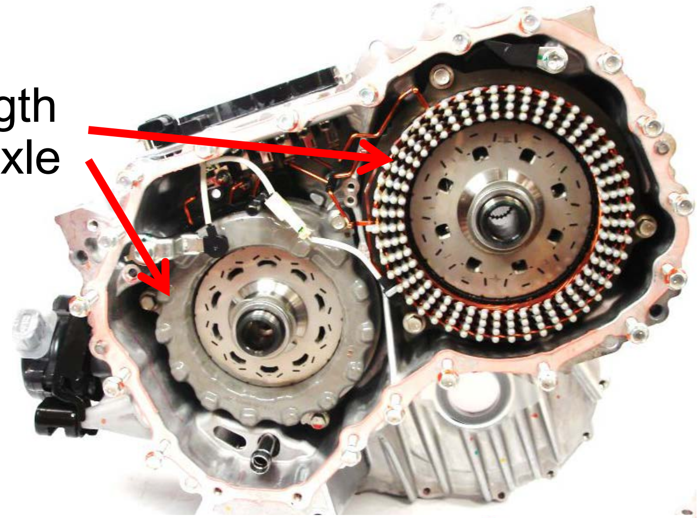
Note: these systems are designed for different scenarios, and some comparisons are not straight forward, but the table can still be informative.

	2004 Prius	2010 Prius	2017 Prius	2007 Camry	2013 Camry	2008 LS600h	2011 Sonata	2012 LEAF	2014 Accord	2016 BMW i3
DC Voltage	500	650	600	650	650	650	270	375	700	355
Current (Arms)	225	170		282		304	212	442	300	375
Motor Power	55	60	53	105	105	160	30	80	124	125
IGBT die Area (mm^2)	131.9	109.4	159.7	120.3	140.8	163.3	99.2	225	185.3	99.3
Number of IGBTs	12	12	6	18	12	12	12	18	12	24
IGBT Total Silicon Area	1582.8	1312.8	958.1	2165.4	1689.6	1959.6	1189.8	4050	2223.12	2382.96
Motor Power/ Total Area	34.75	45.70	55.32	48.49	62.14	81.65	25.21	19.75	55.78	52.46

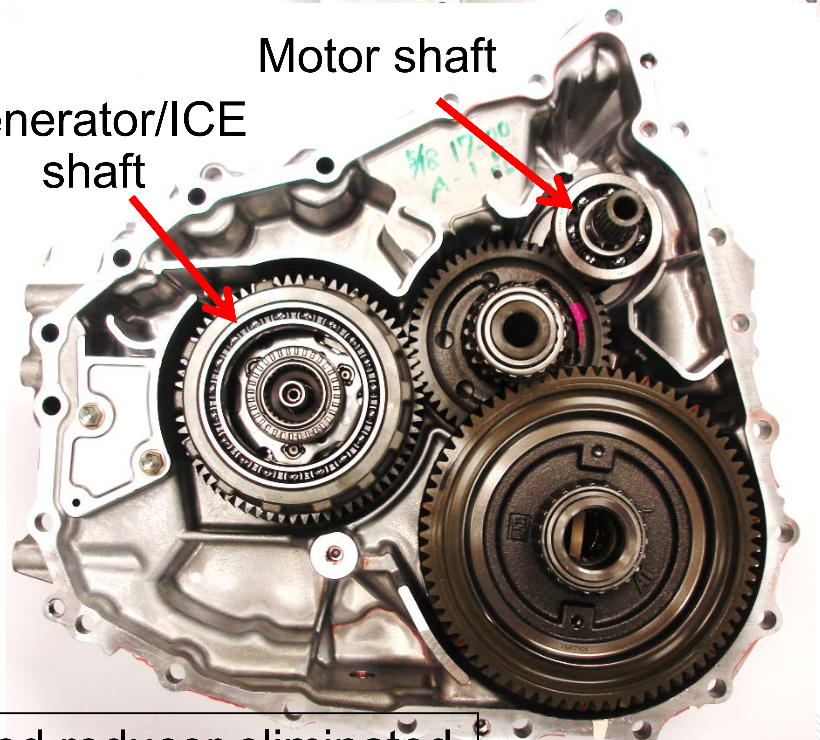


FY17 Accomplishments – 2017 Prius Transaxle

- Motor and generator no longer located on same axis
  - Both have smaller outer diameter and greater length
- Toyota claims 20% mechanical loss reduction transaxle length by 47 mm
- http://pressroom.toyota.com/releases/2016+toyota+prius+technology.htm

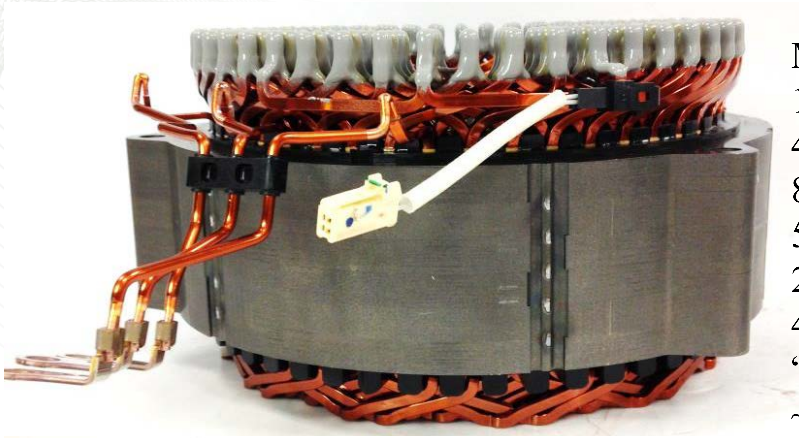


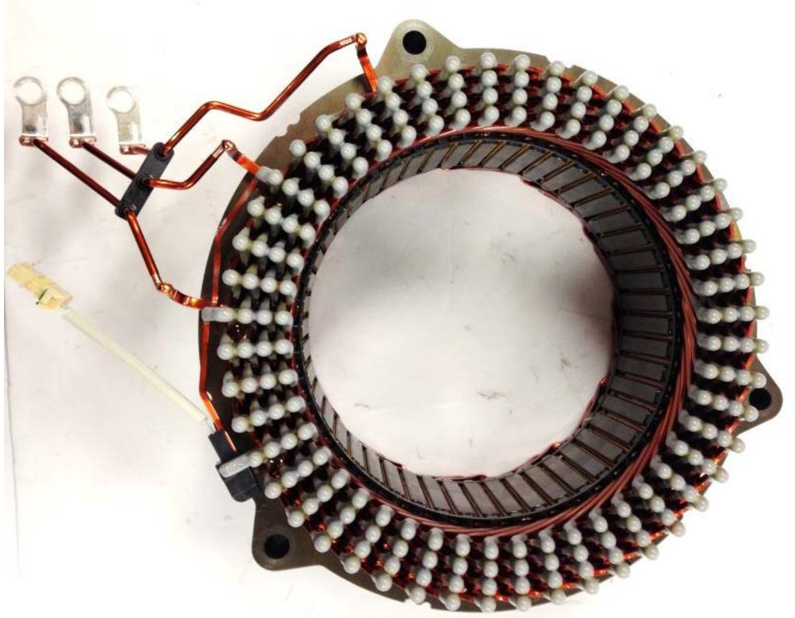
78.4 kg total transaxle mass, as received



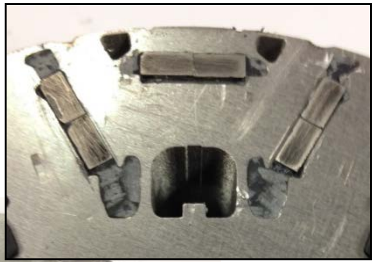
Planetary-based motor speed reducer eliminated

FY17 Accomplishments – 2017 Prius Motor





Motor Stator
11.4 kg
48 slots
8.47” outer diameter (OD).
5.580” inner diameter (ID)
2.35” stack height
4.69” total height
“Hairpin” winding size:
~0.150” x ~0.088



Motor Rotor
6.8 kg including shaft
5.527” OD
2.4” lamination stack height
8 poles, 3 magnets per pole

FY17 Accomplishments - Prius Machine Design Trends

~6.37” Rotor O.D. and ~10.6” Stator O.D.

~5.53” Rotor O.D.
~8.47” Stator O.D.

2002 Prius - 3.5” stack

33 kW, 274VDC, 6000 RPM

2004 Prius - 3.3” stack

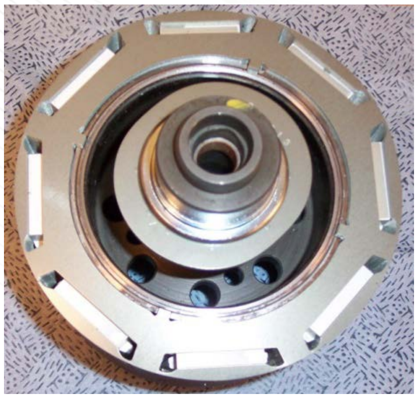
50kW, 500VDC, 6000 RPM

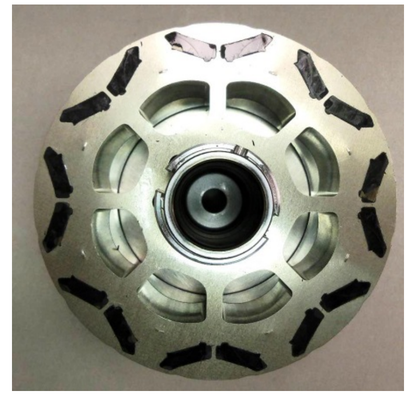
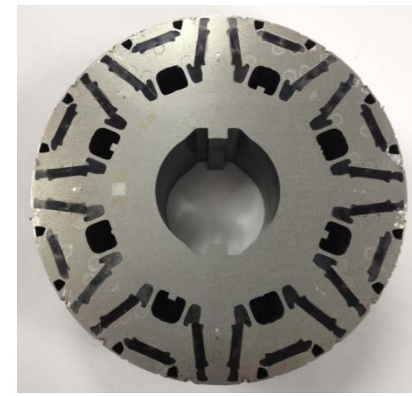
2010 Prius - 2” stack

60kW, 650VDC, 13000 RPM

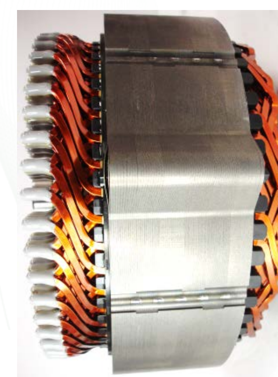
2017 Prius – 2.4” stack

53kW, 600VDC, 17000 RPM



’02,’04, and ’10 stator laminations have very similar OD/ID with 48 slots

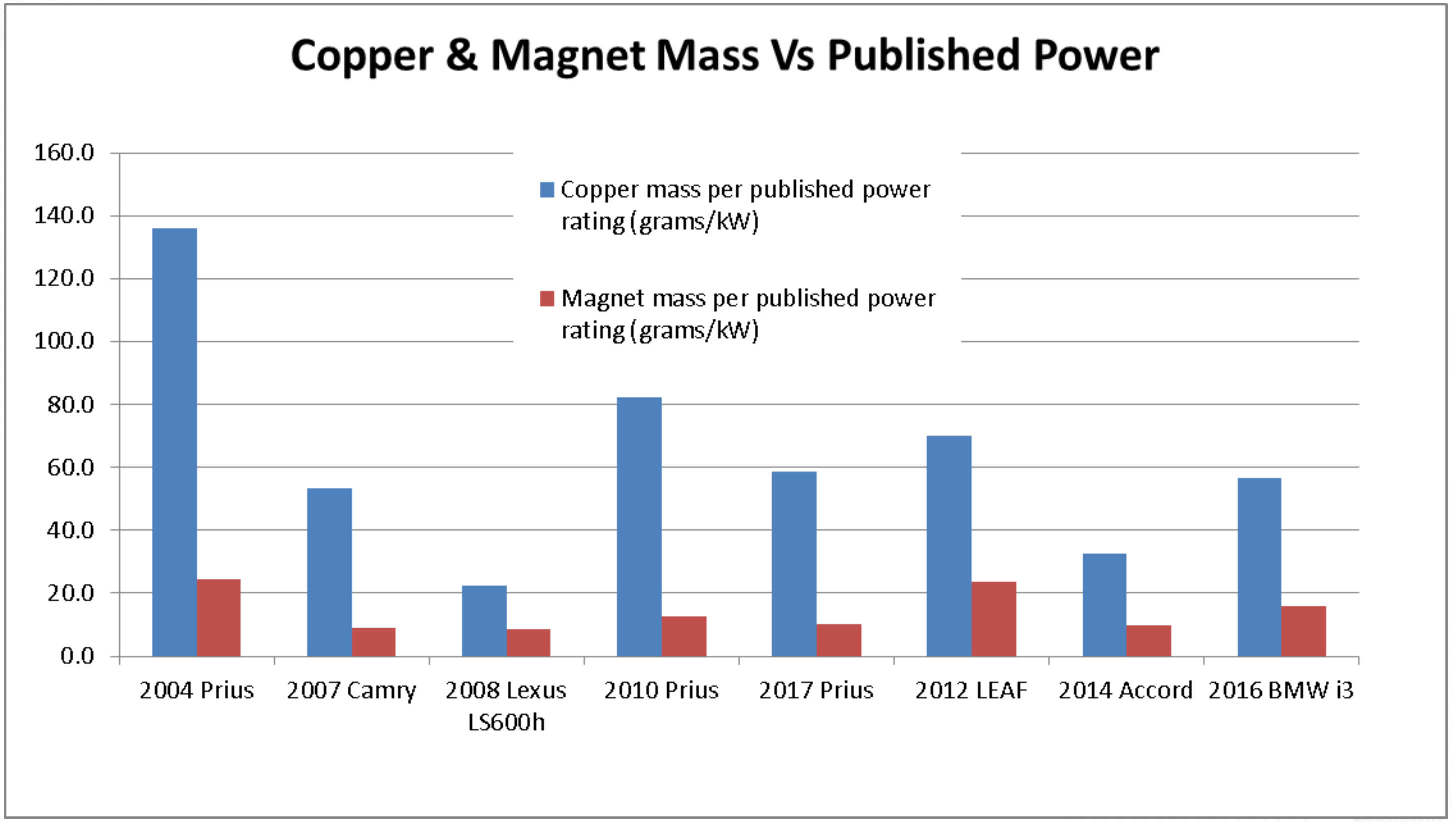



Note: speed reducer required for ‘10 speed level

Increase of voltage, speed, and design quality yielded significant power density (kW/L) and specific power (kW/kg) improvements.

FY17 Accomplishments – Motor Metrics Comparison

Comparison of Copper Mass and Magnet Mass vs Published Power



Note: not necessarily straight-forward comparison, due to various voltages, design for different requirements, etc. However, is still informative.

Responses to Previous Year Reviewers' Comments

- New start, no previous comments.

Partners/Collaborators

Logo	Organization	Role
Argonne NATIONAL LABORATORY	ANL	• Provides system parameters to ORNL from on-the-road tests – Includes extreme hot/cold temperature tests • Examples: – Coolant temperature range and common operation conditions – Battery voltage range and common operation conditions • ORNL provides component efficiency and operational characteristics for AUTONOMIE – Also provides to EPA, automotive manufacturers, and public
NREL NATIONAL RENEWABLE ENERGY LABORATORY	NREL	ORNL provides component efficiency and operational characteristics to NREL for thermal studies.

Remaining Challenges and Barriers for FY17

- Obtaining on the road EDT systems.
- In your accomplishment slides, you may have shown how you've addressed some of the problems with the SOA. In this slide highlight the key remaining challenges and barriers to meeting the project objectives.
- The remaining challenges and barriers should provide justification and support for the future plans in the following slide.

Any proposed future work is subject to change based on funding levels

Proposed Future Work

- **Remainder of FY17**
  - Finalize comprehensive evaluations of 2017 Prius.
  - Complete destructive analysis of 2017 Prius.
  - Complete teardown assessments of 2017 Prius.
  - Design interfaces for and instrument 2017 Prius for testing.
- **FY18**
  - Select commercially available EV/HEV systems relevant to DOE’s VTO mission.
  - Perform standard evaluations of selected system.

Any proposed future work is subject to change based on funding levels

Summary

- **Relevance:** The core function of this project is to confirm power electronics and electric motor technology status and identify barriers and gaps to prioritize/identify R&D opportunities.
- **Approach:** The approach is to select leading EV/HEV technologies, disassemble them for design/packaging assessments, and test them over entire operation region.
- **Collaborations:** Interactions are ongoing with other national laboratories, industry, and other government agencies.
- **Technical Accomplishments:** Tested and reported on more than eight EV/HEV systems including recent efforts on the 2016 BMW i3 and 2017 Prius inverter and motor.
- **Future work:** Complete Accord HEV dynamometer testing and continue evaluating 2017 Prius.

Any proposed future work is subject to change based on funding levels